HIGH FREQUENCY COMMUNICATION SYSTEMS

Lecture 8

Hasan T Abbas & Qammer H Abbasi

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- Array Directivity
- Planar Antenna Arrays
- Feeding Networks
- Software-defined Radio

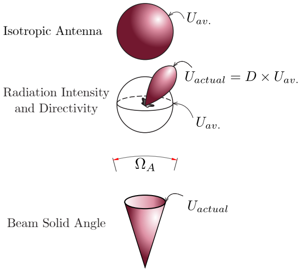
DIRECTIVITY

- Recall *directivity* describes the antenna radiation in a given direction
  - We use the *radiation intensity* $[U(\theta, \phi) = 1/2\,\mathrm{Re}(\vec{\mathbf{E}} \times \vec{\mathbf{H}}^*) \cdot r^2\,\hat{\mathbf{r}}]$ to assess the power radiated in a given direction per unit solid angle
- We define the directivity as:

$$D = \frac{4\pi}{\Omega_A}$$

$$\text{where, } \Omega_A = \oiint |EF(\theta, \phi)|^2 |AF(\theta, \phi)|^2 \mathrm{d}\Omega$$

$$\mathrm{d}\Omega = \sin\theta\,\mathrm{d}\theta\,\mathrm{d}\phi$$



Lets first consider a uniformly excited, uniformly spaced linear array where all the elements are *isotropic* ($EF = 1$). From the previous lecture, we have:

$$|AF|^2 = \left|\frac{\sin N\psi/2}{N\sin\psi/2}\right|^2 \equiv \frac{1}{N} + \frac{1}{N^2}\sum_{m=1}^{N-1}(N-m)\cos m\psi \tag{1}$$

Knowing,

$$\psi = kd\cos\theta + \alpha \implies \sin\theta\,\mathrm{d}\theta = -\frac{1}{kd}\,\mathrm{d}\psi$$

The beam solid angle Ω_A then becomes:

$$\begin{aligned}\Omega_A &= \int_0^{2\pi}\mathrm{d}\phi\int_0^{\pi}|AF(\theta)|^2\mathrm{d}\theta = 2\pi\int_{kd+\alpha}^{-kd+\alpha}|AF(\psi)|^2\left(\frac{-1}{kd}\right)\mathrm{d}\psi \\ &= \frac{2\pi}{kd}\int_{-kd+\alpha}^{kd+\alpha}|AF(\psi)|^2\mathrm{d}\psi \end{aligned}\tag{2}$$

Solving (1) and (2) we get:

$$\begin{aligned}\Omega_A &= \frac{2\pi}{kd}\left[\frac{1}{N}\int_{-kd+\alpha}^{kd+\alpha} \mathrm{d}\psi + \frac{2}{N^2}\sum_{m=1}^{N-1}(N-m)\int_{-kd+\alpha}^{kd+a} \cos m\psi \mathrm{d}\psi\right] \\ &= \frac{2\pi}{kd}\left[\frac{1}{N}\psi\Big|_{-kd+\alpha}^{kd+\alpha} + \frac{2}{N^2}\sum_{m=1}^{N-1}(N-m)\frac{\sin m\psi}{m}\Big|_{-kd+\alpha}^{kd+\alpha}\right] \\ &= \frac{2\pi}{kd}\left[\frac{1}{N}(2kd) + \frac{2}{N^2}\sum_{m=1}^{N-1}\frac{N-m}{m}[\sin m(kd+\alpha) - \sin m(-kd+\alpha)]\right]\end{aligned}$$

Using the trigonometric identity, $\sin(a+b) = \sin a\ \cos b + \cos a\ \sin b$, we get:

$$\Omega_A = \frac{4\pi}{N} + \frac{4\pi}{N^2}\sum_{m=1}^{N-1}\frac{N-m}{mkd} 2\cos m\alpha\ \sin mkd$$

The directivity for broadside and end-fire arrays is thus:

$$D = \frac{4\pi}{\Omega_A} = \frac{1}{\frac{1}{N} + \frac{1}{N^2}\sum_{m=1}^{N-1} \frac{N-m}{mkd} 2\cos m\alpha \, \sin mkd}$$

For arrays such as the *Hanson-Woodyard* arrays, there is an additional renormalisation factor that accounts for the excess phase delay, δ,

$$D_{\text{General}} = \frac{\left| \frac{\sin(N\delta/2)}{N \sin \delta/2} \right|^2}{\frac{1}{N} + \frac{1}{N^2}\sum_{m=1}^{N-1} \frac{N-m}{mkd} 2\cos m\alpha \, \sin mkd} \tag{3}$$

In general, the directivity from (3) can be visualised as:

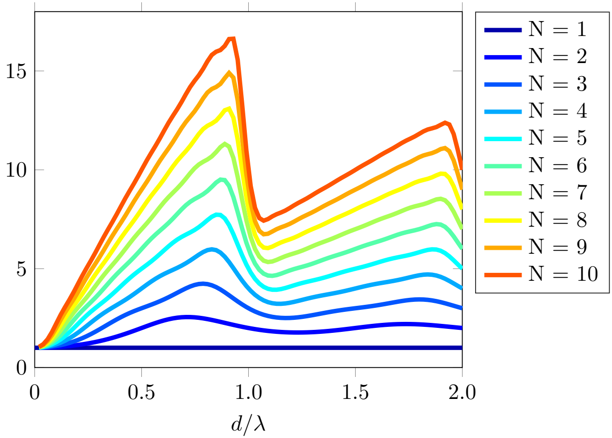


Figure 1: Seeing the directivity as a function of element spacing d and number of elements N.

MULTIDIMENSIONAL ARRAYS

- So far, the 1D arrays we have looked at only yield beamscanning along one angle θ.
- Using multidimensional arrays, we can:
  - Obtain pencil beams
  - Higher directivity and gain
  - Maneuver beams in both elevation and azimuthal planes.
- We can have elliptical or rectangular shapes in the 2D case

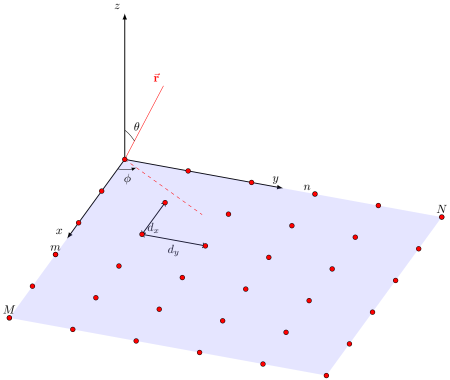


Figure 2: A 2D rectangular array.

Generally, the Array Factor for an 3D array can be described by first expressing the elements in the form of a position vector:

$$\hat{r'}_{mn} = \hat{\mathbf{x}}\, d_{mn} + \hat{\mathbf{y}}\, y'_{mn} + \hat{\mathbf{z}}\, z'_{mn}$$

Then,

$$AF(\theta, \phi) = \sum_{m=1}^{M} \sum_{n=1}^{N} I_{mn} \exp\Big(j \left(k \hat{\mathbf{r}} \cdot \hat{\mathbf{r}'}_{mn} + \alpha_{mn} \right) \Big)$$

In the normalised form, we can write AF as:

$$AF(\theta, \phi) = \frac{\sin M\psi_x/2}{M \sin \psi_x/2} \frac{\sin N\psi_y/2}{N \sin \psi_y/2}$$

where,

$$\psi_x = kd_x \sin\theta \cos\phi + \alpha_x$$

$$\psi_y = kd_y \sin\theta \sin\phi + \alpha_y$$

Considering a 5×5 planar array with element spacings $d_x = d_y = \lambda/2$ and the phases $\alpha_x = \alpha_y = -\pi/(2\sqrt{2})$. The radiation pattern looks like:

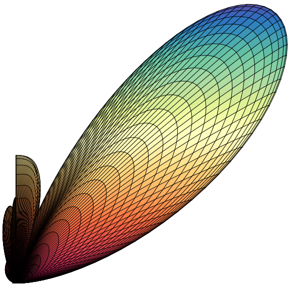


Figure 3: Radiation Pattern in the Cartesian coordinates.

FEEDING NETWORKS

- The main benefit of phased array antennas is there is no need for *mechanical motion*.
  - Beam can be steered using electronics
- A disadvantage is each antenna element *must* have a transmission path to the receiver
  - This is done both via hardware and software

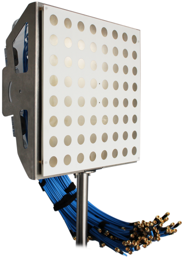
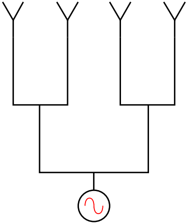


Figure 4: Feeding Cables out of a Massive MIMO Phased Array Antenna

CORPORATE FEEDING NETWORK

- Most common feeding network
  - Also called *parallel* feed
- We have equal line lengths to each element
  - Phase and amplitude are same across the elements
- Corporate feed can be operated at many frequencies
  - We call it wideband as the operation is independent of frequency



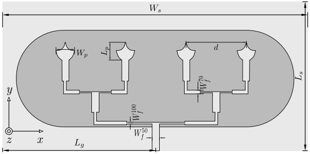


Figure 5: A Planar Inverted Cone Antenna Array [1].

[1] Abdoalbaset al Abohmra et al. “An Ultrawideband Microfabricated Gold-based Antenna Array for Terahertz Communication”. In: IEEE AWPL (2021). ISSN: 1548-5.

- Simplest feeding architecture
  - Phase difference can be easily generated
- However, practically loss occurs along the series line
  - This results in unequal amplitudes across the elements
- By changing the frequency, the electrical line length of the feed is changed.
  - Due to this, we have dispersion that limits bandwidth

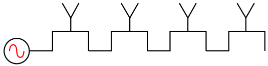


Figure 6: A series feeding network

- Suitable for very large arrays
  - Additional phase shift is introduced commonly through diodes (PIN etc.)
- MEMS based switches can turn a particular arm on or off.
  - Such feeds can withstand high power inputs
- By changing the frequency, the electrical line length of the feed is changed.
  - Due to this, we have dispersion that limits bandwidth

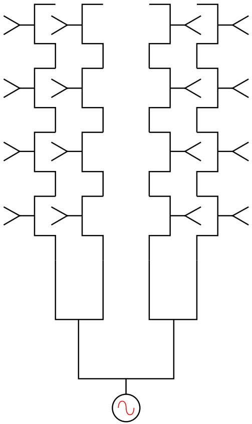


Figure 7: A hybrid corporate-series feeding network

OTHER FEEDING NETWORKS

- For millimetre wave communications, corporate and series feeding architectures become very complicated
- Other techniques such as *sequentially rotated phase* feeding networks are emerging as attractive candidates
    - Each antenna element is physically rotated
    - Additionally, there is a phase shift to each element
- The advantage over corporate feeding network is that the *resonant* response can be obtained at a higher range of frequencies
    - Ensures radiation pattern integrity

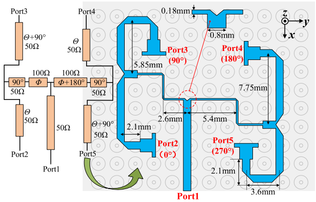


Figure 8: A sequentially rotated phase feeding network [1].

[1] Chaojun Ma, Zu-Hui Ma, and Xiupu Zhang. "Millimeter-Wave Circularly Polarized Array Antenna Using Substrate-Integrated Gap Waveguide Sequentially Rotating Phase Feed", In: IEEE AWPL (2019). ISSN: 1548-5757.

- A communication system consists of many layers of operations.
- The physical layer is the most important of all.
- Typically, physical layer processing is done via dedicated hardware
- Radio is the technology through which signals are wirelessly transmitted and received
- Software-defined radio has some or all physical layer functions implemented via hardware

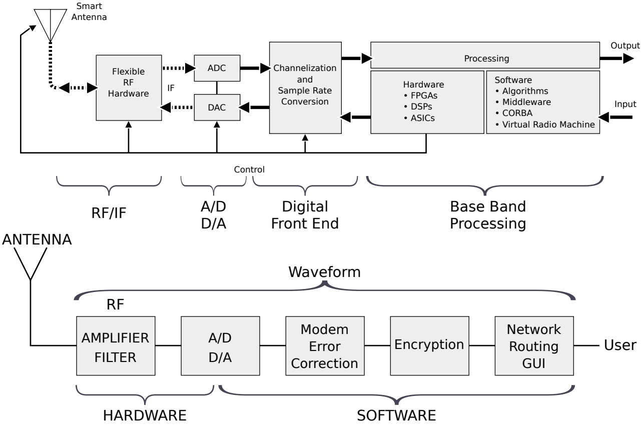


Figure 9: A Typical SDR workflow

- A graphical user interface consisting of *flowgraphs* through which different signal processing functions such as analog-digital conversion can be performed.
- Some additions let us write `Python` codes within each block
- The software is meant to interface with Universal Software Radio Peripheral (USRP) modules to construct a complete communication system.

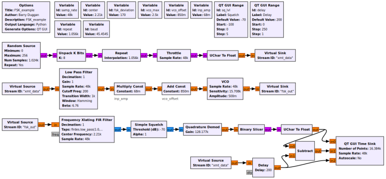


Figure 10: GNU Radio Interface.